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ORGANIC-RICH SOURCE ROCKS OF PENNSYLVANIAN AGE IN THE PARADOX BASIN OF UTAH AND COLORADO

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ABSTRACT

The Paradox basin of southeast Utah and southwest Colorado contains a thick sequence of rocks of Pennsylvanian age which include numerous organic-rich black shales. The richest of these shales are associated with a series of evaporite-carbonate cycles and form the important petroleum source rocks of this basin. Recently the entire Pennsylvanian interval was sampled in two Department of Energy core holes. One of these core holes, the Gibson Dome No. 1 (GD-1) in sec. 21, T. 30 S., R. 21 E., San Juan County, Utah, provided most of the samples used in this report.

The Paradox black shales consist of clay-sized quartz and feldspar, various clay minerals, and a high percentage of calcite and dolomite. The organic carbon content in these rocks is highly variable ranging from about 0.5 to 13.0 weight percent.

Shales in the evaporite-carbonate cycles appear to grade laterally into a prodelta facies, which is part of the Silverton fan delta, located on the southeast margin of the basin. Although the black shales were deposited in an euxinic-evaporitic environment, pyrolysis and extraction data suggests they contain a mixture of type II and III kerogen. The somewhat unexpected abundance of vitrinite in the macerals of these shales suggests a large contribution of terrestrial material associated with fluviatile influxes from the Silverton delta. Vitrinite reflectance values (R_o) in the shales are strongly suppressed and are <0.50% in some samples that have generated as much as 16,000 ppm hydrocarbons.

One of the important source shales, known as the "Gothic," underlies many of the producing carbonate reservoirs in the southern part of the basin. At the GD-1 location the "Gothic" is 32 ft (9.7 m) thick and has generated at least 4,970 bbls of oil per acre. This shale thickens to over 160 ft (48.7 m) near the Silverton fan delta complex where it may intertongue with porous delta front and distributary channel sandstone reservoirs. This intertonguing relationship suggests a potential petroleum exploration target; however, the quality and quantity of kerogen in the shale may decrease in this part of the basin.

INTRODUCTION

During Pennsylvanian time, possibly as early as the Atokan, a rapidly subsiding northwest-southeast trending basin located in southeast Utah and southwest Colorado (Figure 1) began to fill with a cyclical sequence of thin dark colored organic-rich shales, limestones, dolostones, and anhydrites. This basin, known as the Paradox, was characterized by pronounced restriction of marine circulation almost from its inception. Strong continuous uplift in highlands bordering the basin on the northeast combined with mildly positive movements of semi-emergent land masses on the southwest and northwest margins intensified the early euxinic-evaporitic conditions. This eventually gave rise to deposition of thick beds of halite and potash salts as well as continued deposition of the other facies. This evaporitic sequence may have originally reached a maximum depositional thickness of 7,000 to 8,000 ft (2131-2435 m); locally, however, these thicknesses have been greatly modified by flowage. By late Pennsylvanian time, the basin had been filled essentially

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to sill depth by rapid evaporite deposition so that basin circulation improved and the euxinic conditions were modified to become predominantly open marine.

The principal petroleum source rocks of the Paradox basin are black shales, which were deposited during a euxinic-evaporitic phase. These shales have been responsible for a cumulative petroleum production of about 400 million barrels (53.6 million metric tons) of oil and 1 TCF (28.4 billion m^3) of gas (Baars and Stevenson, 1982). This petroleum is reservoired principally in stratigraphic traps in carbonate rocks interbedded with the source rocks and in older carbonates, which are structurally juxtaposed with the source rocks. However, a few single well fields have had significant production from fracture systems developed in the source rocks.

Incomplete Pennsylvanian sequences, which include some of the black shales, crop out at only a few localities around the basin margins and in some of the complexly deformed diapiric masses associated with the salt anticlines in the northeast basin sector. Opportunities for detailed subsurface studies of the entire Pennsylvanian sequence have been somewhat restricted until recently when two deep core holes, drilled by the Department of Energy (DOE), completely penetrated these rocks. These two DOE holes are in San Juan County, Utah, and include the Gibson dome no. 1 (GD-1) in sec. 21, T.30S., R.21E., and the Elk Ridge no. 1 (ER-1) in sec. 30, T.37S., R.19E. (Figure 1). The GD-1 hole, which is on the southeast plunge of a small salt anticline known as Gibson Dome, was cored continuously from about 200 ft (60.9 m) below ground surface to a depth of 6,500 ft (1978.7 m). Surface rocks at this locality belong to the Permian Cutler Group

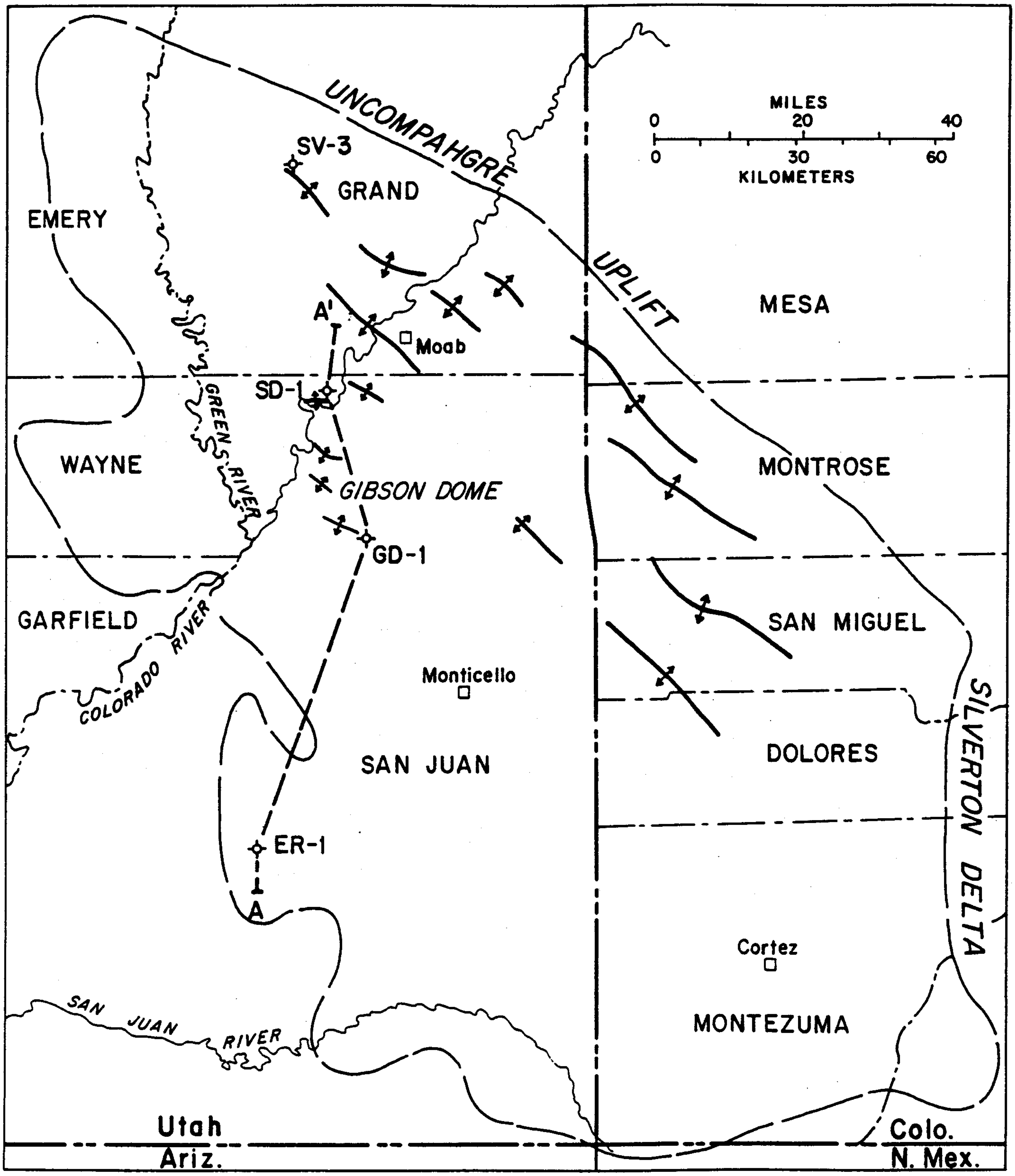


Figure 1. Index map showing boundaries of the Paradox basin (zero edge of halite), locations of salt anticlines, the Silverton fan delta complex, the GD-1, ER-1, SD-1, SV-3, and KIS-1 core holes, the Texasgulf Inc. potash mine, and the line of section for Figure 4.

so that the hole penetrates the entire Pennsylvanian sequence and is bottomed in the Mississippian Ouray Formation.

In this report, the principal source of data pertaining directly to the source rocks was the GD-1 hole. In addition some data came from the ER-1 hole, the DOE Salt Valley no. 3 (SV-3) in sec. 5, 23S., T.20E., Grand County, Utah, the Delhi-Taylor Oil Corp. Shafer Dome no. 1 (SD-1) in sec. 15, R.27S., R.20 E., San Juan County, Utah, the Kissinger Petroleum Corp. no. 1-4, (KIS-1) in sec. 4,T.38N., R.18W., Montezuma County, Colorado, and the Texasgulf Inc. potash mine near Moab, Utah.

The work reported on here represents a very limited sampling of source rocks that extend over an area of about 15,000 mi^2). A regional sampling program was recently begun by the U.S. Geological Survey which should result in a much more complete characterization of the Pennsylvanian source rocks. Despite its obvious regional shortcomings, this report represents the first published investigation of a complete vertical sequence of these source rocks in the Paradox basin.

SOURCE ROCKS AND THE EVAPORITE ENVIRONMENT

Pennsylvanian rocks in the Paradox basin were deposited in several environments. However, it is the evaporite environment that was responsible for the greatest accumulation of organic matter, which became the ultimate source for most of the region's production. For that reason, it seems particularly appropriate to discuss the physical, biological, and geochemical parameters of this environment before delving into the organic geochemistry of the Paradox basin.

Recognition that the evaporite environment promotes the entrapment and preservation of large amounts of organic matter came some years ago (Peterson and Hite, 1969), but it was only recently that the effectiveness of the environment in producing organic matter was realized (Kirkland and Evans, 1981). The solubility of oxygen is extremely low in highly concentrated brines (Copeland, 1967; Hite, 1970; and Kinsman and others, 1973). In relatively deep evaporite basins, mixing of oxygen into the brine by surface turbulence does not effect the deeper brine layers, thus inhibiting aerobic decay. Preservation of organic matter is also enhanced by anaerobic sulfate reducing bacteria which utilize only a small part of the total organic matter in their metabolism but produce enough H_2S to limit the activities of other halophillic bacteria. Most of the phytoplankton and zooplankton that reach the interior of an evaporite basin through marine influx are preserved in the heavy brines. Although the volumes of influx may be quite large, the amount of organic matter that accumulates in the basin in this manner is relatively small. A much larger volume of material is actually generated within the basin. Measurements of rates of biomass generation in the evaporite environment are somewhat limited but even so, it is now known that it is capable of productivity exceeding all other naturally occurring unpolluted aquatic environments. A small brine pond along the Gulf of Aqaba, the so-called "Solar Lake," is known to have a remarkable biomass production of 4,960 mg $Cm^{-3}d^{-1}$ when its brine is strongly stratified (Hirsch, 1980). Similar high production rates are indicated for the Great Salt Lake where the average standing biomass, which is dominated by halophillic bacteria, is 300 g/m^3 (Post, 1977). There is, however, still some question about the optimum brine concentration for greatest biomass production. Most measurements have been made in solar ponds where the brine does not greatly exceed the saturation point for halite. It is possible that biomass production might be even higher in brines of higher salinities which are near or at, saturation for potash salts. Analyses of three brine samples from the Alviso salt ponds at the southern end of San Francisco Bay gave the following results:

Sp. gr.	Saturation field	Organic Carbon (ppm)
1.16	Gypsum	223
1.21	Halite	249
1.30	Close to potash	2,417

These results would suggest that organic productivity, which in this case involves mostly photosynthetic halophilic bacteria, is an order of magnitude higher in brine concentrated close to the field of potash precipitation. Another interesting aspect of this organic material is the fact that much of it is in solution. According to Larsen (1980), this results from death and decay of algae at lower salt concentrations which subsequently returns soluble organic material to the brine (autolyzation). In addition to determining the organic carbon for the 1.30 sp. gr. Alviso Pond brine, a 300 g sample of the brine was freeze dried and extracted with benzene. A total of 10.62 mg of bitumen was extracted, which calculates back to a bitumen content of 66 ppm in the original brine. The extract was then fractionated on a silica gel column giving the following results:

19.1%	Saturated hydrocarbons
12.4%	Aromatic hydrocarbons
64.2%	Resins, asphaltic, and high molecular wt. compounds containing N, S, and O
4.3%	Not recovered

From these data it can be concluded that evaporite basins, particularly deep basins that contain a potash facies, are ideally suited for the development of petroleum source rocks. It has been noted in the Paradox basin that potash ore contains as much as 3,000 ppm extractable hydrocarbons (Peterson and Hite, 1969). Another favorable aspect, which is somewhat overlooked, is the mobile source constituted by the organic soups that form at high salinities. When they are first deposited, halite beds can have porosities as high as 40 percent (Ver Planck, 1958). When these beds are compacted, as the result of burial, the organic-rich pore fluids can be expelled into overlying rocks which may have favorable reservoir characteristics. Because the organic soups are largely comprised of algal and bacterial cell walls, plus the products of autolyzation, conversion rates to hydrocarbons during catagenesis should be quite high.

In the Paradox basin, refluxion of heavy organic-rich evaporite brines may have charged associated porous carbonate reservoirs with petroleum precursor products similar to those previously described. However, the most significant volumes of organic matter accumulated during a high sea level stage when evaporite minerals had ceased to form. Even at this stage salinities were still quite high, and all the biochemical parameters typical of the evaporite environment were still in force. Accumulation of organic-rich sediments during this period may have been more the result of efficient preservation and slow sedimentation rates (starved basin) rather than high biomass production. Another important factor, which will be discussed in following sections, is that fluviatile contributions seem to have carried large amounts of organic matter into the basin at this time.

STRATIGRAPHY

Rocks of Pennsylvanian age in the Paradox basin are characterized by some rather complex vertical and horizontal facies changes. Carbonates and evaporites are the major facies of this sequence; however, a small but important fine-grained siliciclastic component is also present. The evaporite facies transcends time lines, going from shelf to inner basin, so that some informally named time-stratigraphic units, which are entirely within member boundaries on the shelf, are outside these boundaries deeper in the basin. For detailed treatment of the problems of applying nomenclature to these rocks, the reader is recommended to Baars and others (1967) and Hite and Buckner (1981). For this paper, the terminology of Bass (1944) will be used along with the addition of some informal names for stratigraphic units of less than formation or member rank (Figure 2).

Molas Formation

The oldest Pennsylvanian rocks in the Paradox basin belong to the Molas Formation and are Morrowan to Atokan in age. This formation consists of a red paleosol developed on a karstified surface on the underlying Mississippian carbonates. The upper part of the formation is probably marine and represents reworking of the paleosol by the first incursion of the sea into the Paradox basin. The Molas reaches a maximum thickness of 250 ft (76.1 m) in the southeast corner of the Paradox basin. The formation was deposited in a strongly oxidizing environment so that it seems unlikely that it would contain potential source rocks.

Hermosa Formation

When an evaporite facies is present the Hermosa Formation can be subdivided into the Lower Member (carbonate facies), the Paradox Member (evaporite facies), and the Upper Member (carbonate facies).

The Lower Member (Pinkerton Trail Formation of Wengerd and Matheny, 1958) of the Hermosa Formation overlies the Molas Formation. The member is Atokan in age and is as much as 400 ft (121.8 m) thick along the southwest margin of the Paradox basin. The member thins to less than 50 ft (15.3 m) in the deepest part of the basin as the result of lateral transition into the predominately halite facies of the Paradox Member. At the GD-1 locality, the Lower Member consists of a basal gray calcareous shale, followed by a sequence of dark-gray, highly radioactive shales, anhydrites, and dolostones. Some of the shales are organic-rich but little is known about their source rock potential. Most of the anhydrites present at the GD-1 locality pass into a halite facies deeper in the basin. As used in this paper, the boundary between the Lower Member and the overlying Paradox Member is the base of the lowermost halite-bearing evaporite cycle.

The base and top of the Paradox Member of the Hermosa Formation is usually defined by the first and last halite beds. In the deep part of the Paradox basin, the member consists of 29 identifiable evaporite cycles (Hite, 1960), and its maximum depositional thickness was probably about 7,000 ft (2130.9 m). These cycles are bounded by disconformities and when complete the sequential order from the base upward is (a) anhydrite, (b) very silty fine grained dolomite, (c) silty calcareous black shale, (d) silty fine grained dolostone, (e) anhydrite, and (f) halite with or without potash salts. With the exception of the black-shale unit, all of the elements of the cycle were deposited in response to salinity changes in the basin brine. In the deep part of the Paradox basin, the

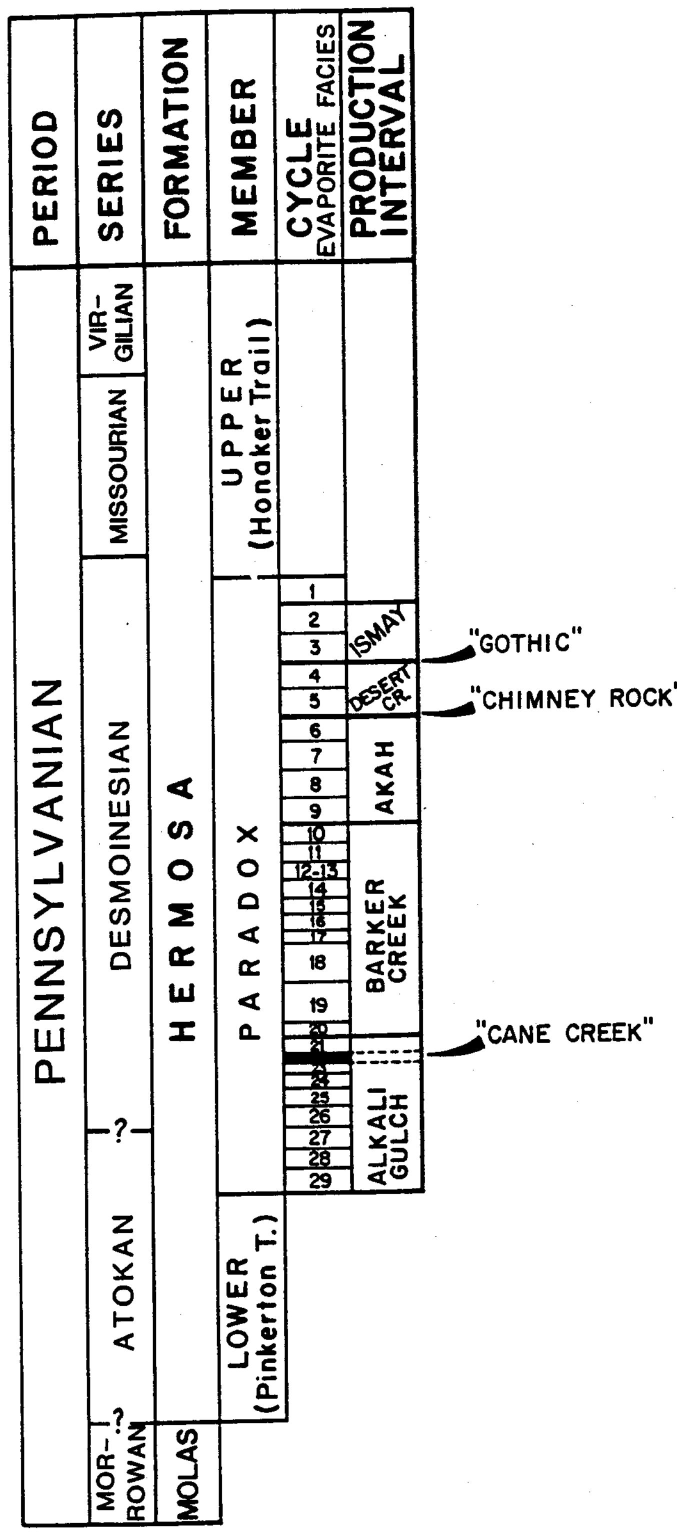


Figure 2. **Stratigraphic nomenclature of Pennsylvanian rocks in the Paradox basin. As shown here the boundary between the Upper (Honaker Trail) and Paradox Members is the top of evaporite cycle 1. Due to lateral facies changes, this boundary can move stratigraphically downward depending on the location in the basin (see Figure 3).**

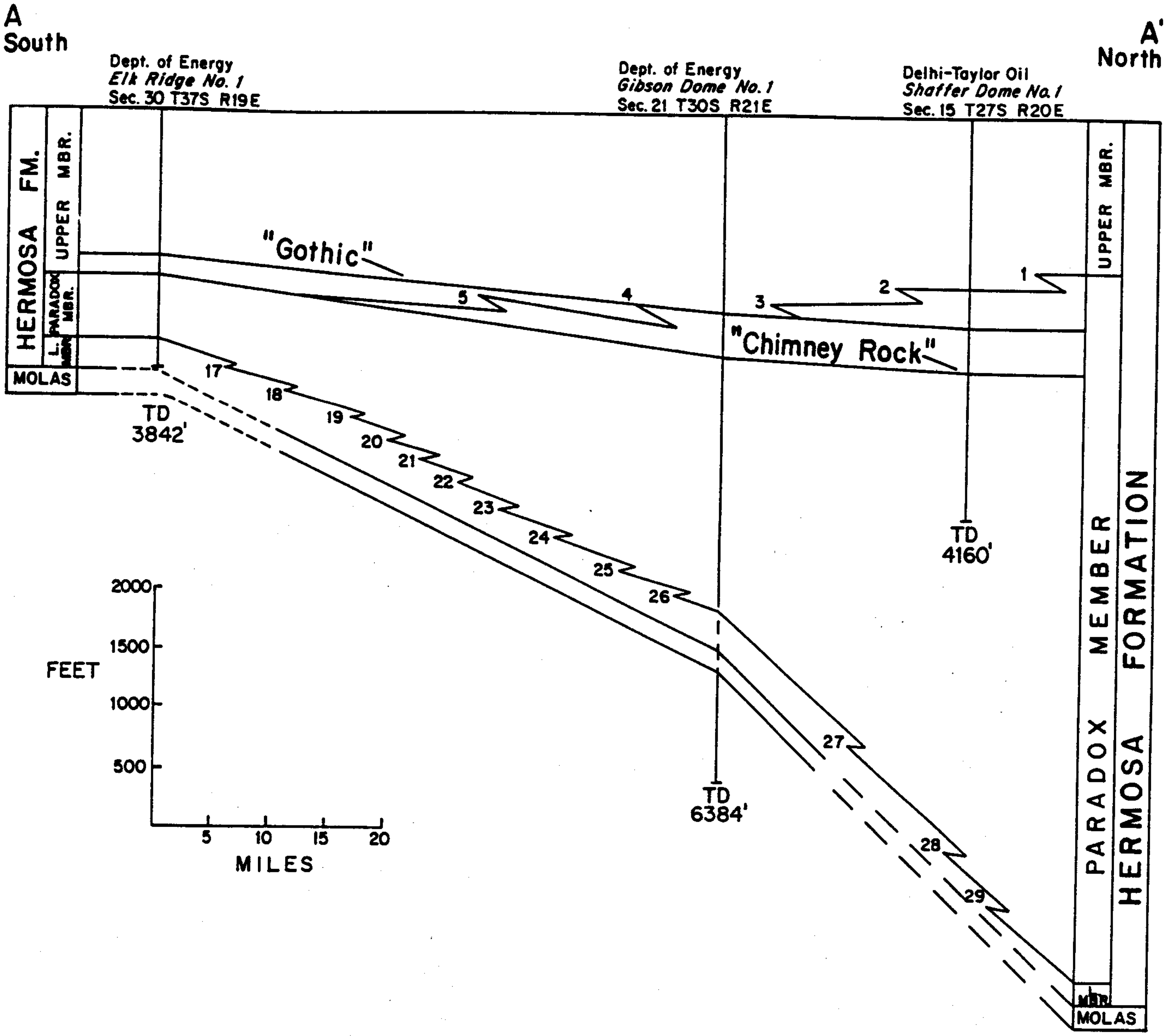


Figure 3. **Diagrammatic north-south stratigraphic cross section through Pennsylvanian rocks in the ER-1, GD-1, and SD-1 core holes. Numbers refer to evaporite cycles of the Paradox Member and indicate depositional limits of the halite unit in the cycle. Two black shales known as the "Gothic" and "Chimney Rock" are shown passing from the evaporite facies of the Paradox Member into the dominately carbonate facies of the Upper Member.**

cyclical sequence consists of up to 80 percent halite. Going from the basin deep to basin shelf, the amount of halite in the cycles diminishes while the percentage of dolostone and anhydrite increases. In the GD-1 hole, which is located midway between basin deep and shelf, the cumulative thickness of the lithologies in these cycles (Hite, in press) are as follows:

	Feet	Meters
Halite and minor potash	2,025	617.2
Anhydrite	305	3.0
Dolomite	127	38.7
Clastics (black shale)	125	38.1

The black shales of the evaporite cycles are time synchronous units of wide regional extent, are radioactive, and have highly recognizable signatures on gamma-ray logs. As a result, these shales can be correlated from the evaporite facies of the Paradox Member into a laterally equivalent carbonate facies of both the Upper and Lower Members of the Hermosa Formation. Where this is possible, carbonate cycles in the Upper and Lower Members can be identified by the same numerical designation used for equivalent cycles in the evaporite facies (Figure 3). In the GD-1 hole, because of its position in the basin, the Paradox Member includes only evaporite cycles 4 through 26 (Figure 3). Some of the black shales in the evaporite-carbonate cycles have been given informal names by the petroleum industry. For example, the shale in cycle 3 is also known as the "Gothic". Another shale at the base of cycle 5 is commonly called the "Chimney Rock". Both of these shales underlie major petroleum producing reservoirs elsewhere in the basin.

The Upper Member (Honaker Trail Formation of Wengerd and Matheny, 1958) of the Hermosa Formation is predominately limestone and is late Desmoinesian to Virgilian in age, but locally may range into the Wolfcampanian (Permian). Its upper boundary is not always clearly definable because it is transitional with the overlying Cutler Formation. The lower boundary of the member is well defined by the top of the first halite bed in the underlying Paradox Member. It ranges in thickness from about 1,000 ft (304.4 m) to 1,700 ft (517.5 m). This unit was deposited in relatively shallow waters after the initially deep Paradox basin had nearly filled with rapidly deposited evaporites (Hite, 1970). Shoaling conditions, plus higher energy environments combined to create erratic sedimentation patterns throughout most of the member; except near its base where black shales of the evaporite-carbonate cycles are present. These black shales define intervals in the carbonate facies, on the southern and southwest shelf of the basin, which contain extensive petroleum reservoirs. The names of these intervals and their equivalent cycle members are shown on Figure 2.

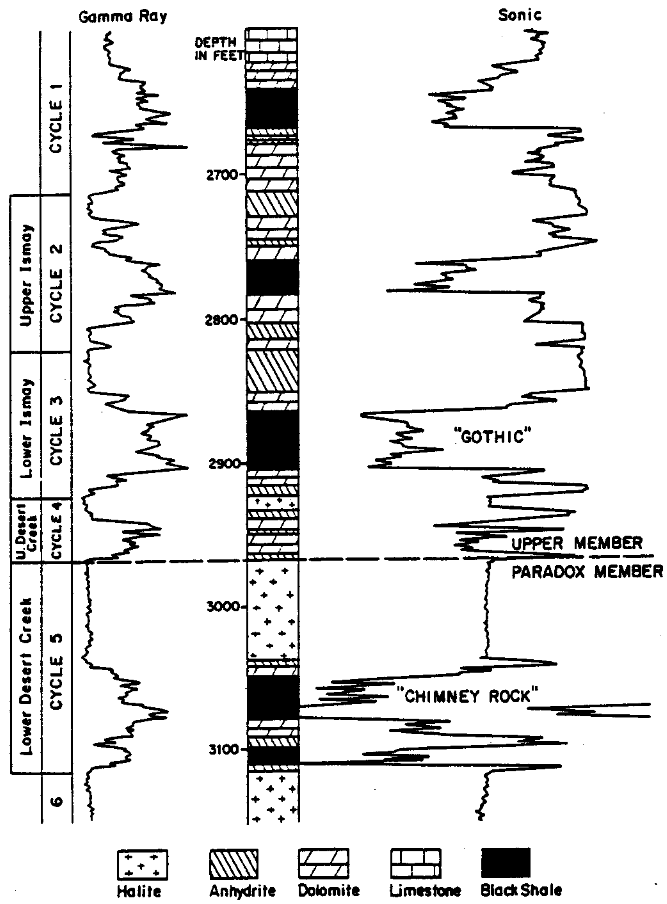


Figure 4. Lithology and stratigraphy in the GD-1 core hole at the boundary between the Paradox and Upper Member of the Hermosa Formation.

SOURCE ROCK MINERALOGY AND SEDIMENTATION

The most important Pennsylvanian source rocks in the Paradox basin are the black shales associated with the evaporite facies of the Paradox Member. These shales in general, consist of about equal amounts of carbonate minerals, clay-sized quartz, and various clay minerals. In general, the carbonate mineral fraction is equally divided between dolomite and calcite. The clay mineral assemblage is dominated by discrete illite but also includes minor amounts of chlorite, corrensite, and mixed-layer chlorite-trioctahedral smectite (Bodine and Rueger, 1984). Other common accessory minerals in the shales include feldspars and finely disseminated halite and anhydrite. In certain parts of the basin, clay minerals are present in some shales in only trace amounts and the approximate order of abundance of rocks forming minerals is quartz, calcite, and dolomite. Thus, the term "shale" is somewhat of a misnomer when applied to these rocks; however, this usage is firmly entrenched so the term black shale will be used throughout this report for rocks whose modifiers might include calcareous, dolomitic, silty, argillaceous, and carbonaceous.

Three black shales are particularly important source rocks in the Paradox basin. These shales are elements of evaporite-carbonate cycles 2, 3, and 5 (Figure 4). They are important because they contain major amounts of kerogen and immediately underlie some of the most prolific petroleum reservoirs in the basin. One of these shales was singled out for detailed study in terms of minerals facies, sedimentation patterns, and organic geochemistry. This unit, which is part of Paradox cycle 3 and is informally called the "Gothic" shale by the petroleum industry, can be readily identified on gamma-ray logs throughout most of the Paradox basin. In addition, cores from several holes which penetrated this unit at widely separated localities were available for study.

The mineralogy of the "Gothic" shale was studied in composited samples from splits of the widely separated drill holes by X-ray diffraction (XRD) analysis (Figure 5). Although sampling in the GD-1 hole was not complete in this interval because of core loss, the uniform distribution of minerals in those samples available for analysis suggests that the data obtained are representative of the complete interval. A comparison of the relative amounts of major rock-forming minerals, based on peak height for the principal reflection of each mineral, shows several prominent differences in regional distribution of mineral facies. As might be expected, dolomite is most abundant in the Shafer Dome hole (SD-1), which is located in the deeper distal reaches of the basin where evaporitic conditions were most severe. The dominant carbonate in the Elk Ridge hole (ER-1) is calcite suggesting a closer affinity to normal marine conditions and the possibility of a nearby marine accessway. The quartz distribution (highest in ER-1) also supports possible clastic transport from a marine accessway on the southwest side of the basin. Whole rock XRD analysis of the ER-1 samples detected only trace amounts of clay minerals. Much greater concentrations of clay minerals were present in the GD-1 and SD-1 samples, which also suggests a different clastic source area for ER-1.

The black shales of the Hermosa Formation are lithic components of a series of evaporite-carbonate cycles (Hite, 1960 and 1961). These cycles, which are developed most completely in the inner basin evaporite facies of the Paradox Member, show vertical sequences of evaporite layers which correspond to the expected order of solubility products from evaporated seawater (Usiglio, 1849). To obtain the frequently repeated sequential order, the evaporite brines had to undergo many

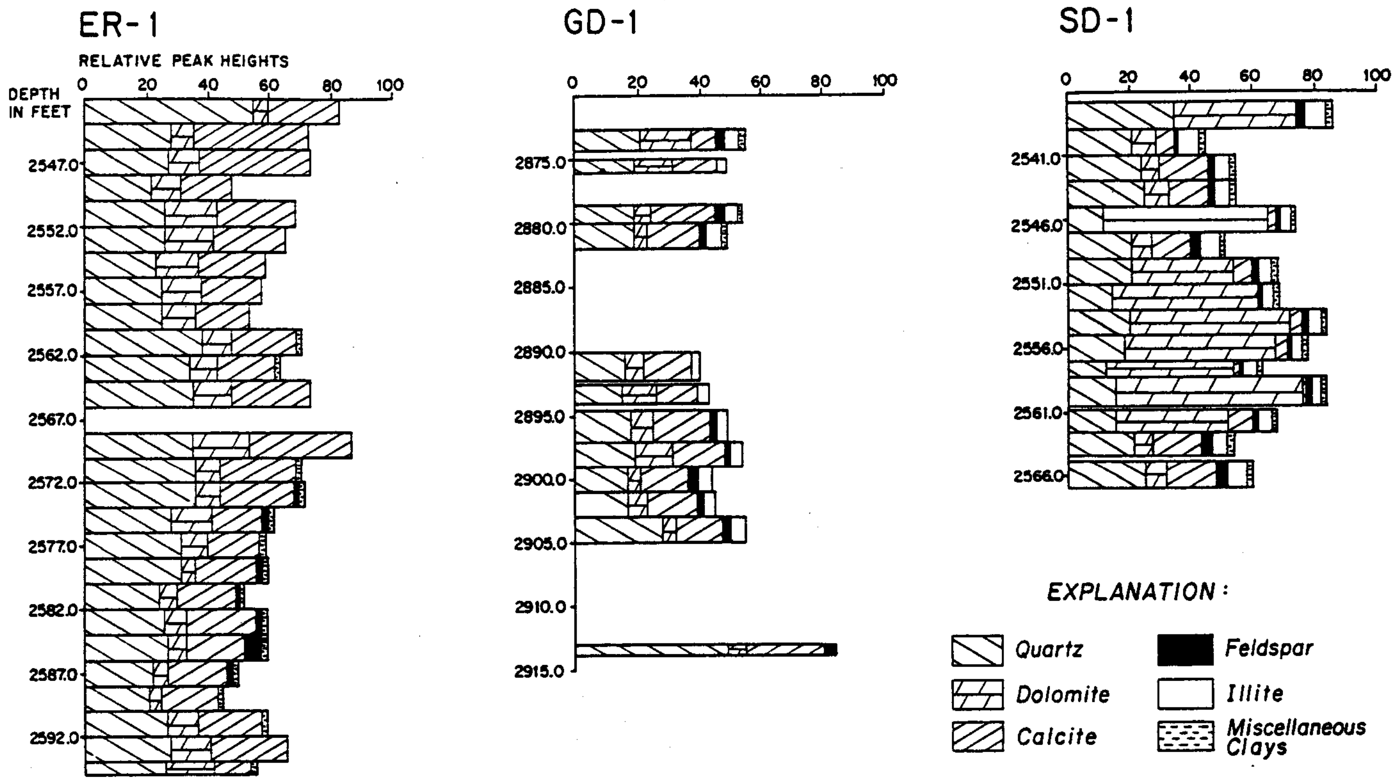


Figure 5. Mineralogy, as determined by X-ray diffraction analyses, of the black shale unit ("Gothic") in evaporite-carbonate cycle 3 (Lower Ismay) of the Hermosa Formation in the ER-1, GD-1, and SD-1 core holes. Bar graphs show relative amounts of the major rock-forming minerals.

periods of progressive salinity increase followed by dilution. These salinity changes have been ascribed to periodic decrease or increase of marine influx as the result of (a) eustatic rise and fall of sea level (Peterson and Hite, 1969; Hite, 1970), or (b) a local tectonic pulse which choked marine access ways with clastic sediment (Fetzner, 1960).

Most of the black-shale facies of the Paradox cycles seems to be the result of clastic influx from land areas bounding the basin on the southeast. Many of the shales, especially those near the top of the Paradox Member, thicken markedly toward this side of the basin. For example, the "Gothic" shale which is 42 ft (12.8 m) thick in the GD-1 hole thickens to over 160 ft (48.7 m) along the southeast edge of the basin (Figure 6). Northwest trending paleo highs also strongly influenced sedimentation patterns in this same area. The clastic ratio maps of Fetzner (1960) show clastic input from this part of the basin, which he referred to as the Silverton embayment, beginning in moderation but intensifying throughout the deposition of the Hermosa Formation. The source area was apparently the San Luis uplift which is now recognized to be a tectonic feature separate from the Uncompahgre uplift (Baars and Stevenson, 1984).

The pronounced worldwide cyclicity of the Pennsylvanian period, combined with direct evidence of major periods of glaciation in the southern hemisphere (Sanford and Lange, 1960), make an appealing case for glacio-eustatic sea level changes as the control for the salinity variations in the Paradox cycles. However, the black-shale facies of the cycles represents clastic influx from the land and, thus, would not seem to be directly related to the associated chemical facies. Despite the seemingly generic differences of these facies within the cycles, there must be some common depositional control because the black shale always occupies the same position in the cycle. This position indicates that the clastic influx came at the time of lowest salinity, or when the basin was receiving maximum input of seawater.

The clastic facies on the southeast basin margin, which is age equivalent to the evaporite-carbonate cycles, was first recognized by Fetzner (1960) as being part of a large fan delta complex, which he named the Silverton embayment clastic delta. In this report, the complex will be referred to as the Silverton fan delta. Spoelhof (1976) made a detailed investigation of the complex and noted its cyclical nature. He was able to define 19 major depositional cycles, which he suggested were the product of eustatic sea level changes. A typical Spoelhof cycle, which includes products of both deltaic and marine sedimentation, can be described as follows:

Marine limestone (next cycle)

(A) Delta plain facies — red and brown shale, siltstone, and fine-grained sandstone with carbonaceous plant debris and rhizoconcretions.

(B) Distributary channel facies — poorly sorted, coarse-grained sandstone with a frequent scour base and log imprints.

(C) Distal bar or delta front facies — well-sorted, fine- to medium-grained, arkosic, sandstone with large-scale cross-stratification and plant fragments.

(D) Prodelta facies — dark-gray marine shale or siltstone with a sparse fauna that includes foraminifera, ostracods, and brachiopods.

(E) Shallow marine — gray fossiliferous marine limestone. Forms base of cycle.

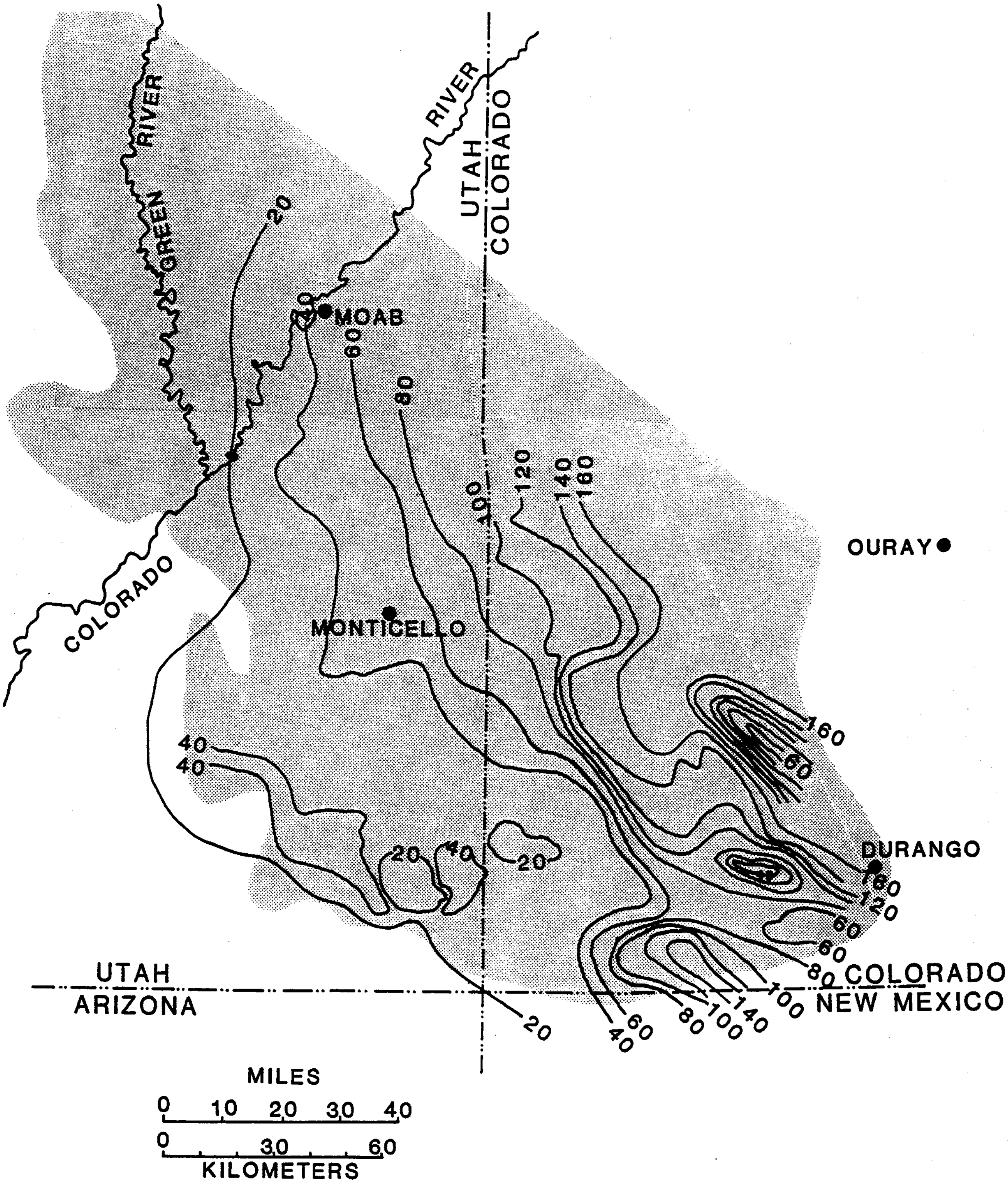


Figure 6. Generalized isopach map of the black-shale unit ("Gothic") in evaporite-carbonate cycle 3 (Lower Ismay) of the Hermosa Formation. Contour interval is 20 ft (6 m). Scale of map and high density of drilling in many localities precludes showing well control. Note the influence on sedimentation in the southeast sector by a series of northwest-trending paleo highs.

The similarities between the cycles of the Silverton fan delta and deltaic cycles of Upper Pennsylvanian age in southeast Kansas (Moussavi-Harami, and Brenner, 1984) are striking. In both areas, a cycle begins with rising sea level and deposition of normal marine limestone. Further rise in sea level produced the dark shales of a prodelta facies. Somewhere in the prodelta facies, sea level began to fall and the lowest sea level stand is represented by a delta plain facies.

When the clastic cycles of the Silverton fan delta are

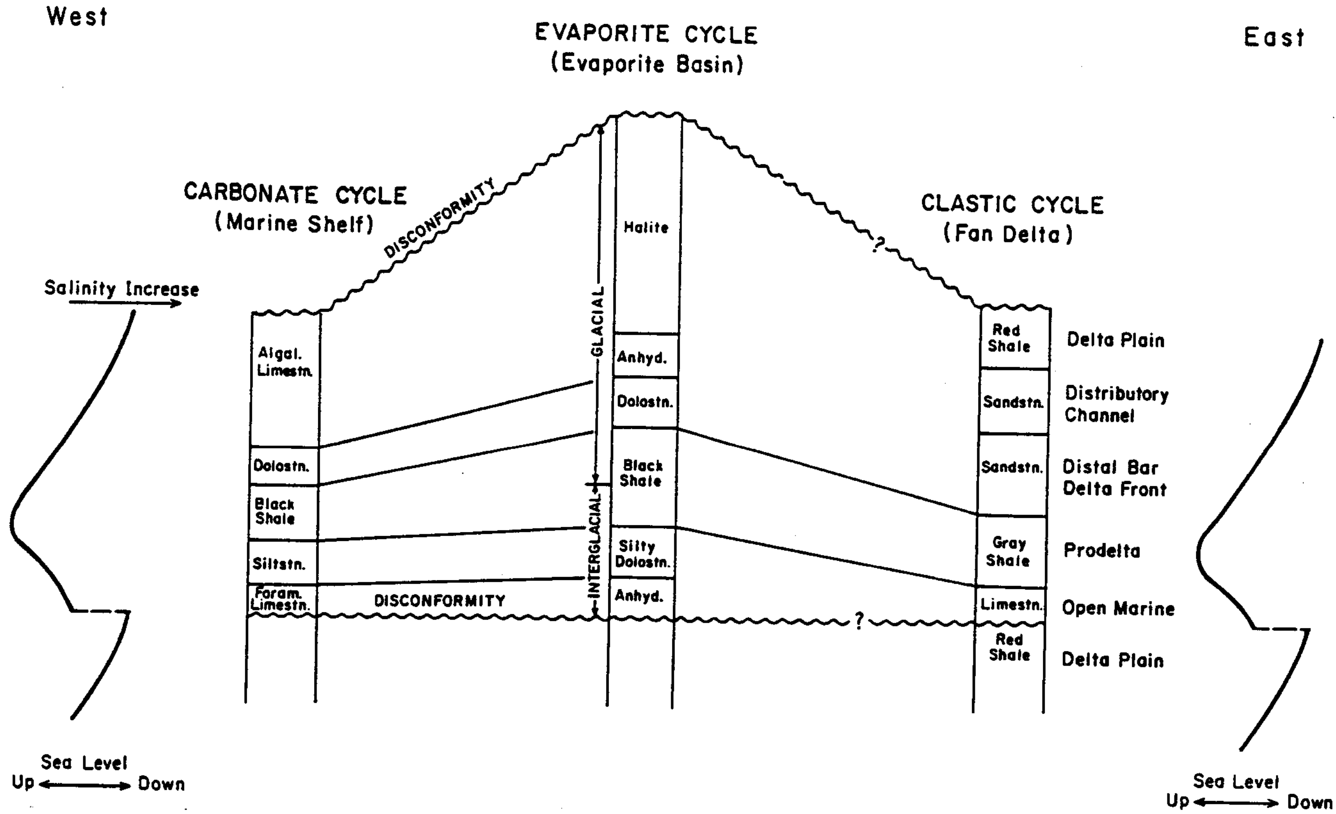


Figure 7. Diagrammatic correlations of facies in "idealized" carbonate, evaporite, and clastic cycles in Desmoinesian rocks of the Paradox basin. The clastic cycle is from Spoelhof (1976). Curves show relative sea level and salinity conditions during the deposition of each facies. Based on a proposed glacio-eustatic control of cyclicity, the cycle elements are divided into interglacial and glacial phases.

related to sea level change, they can be correlated, at least in part, with the evaporite carbonate cycles (Figure 7). A comparison of these cycles suggest that the black-shale facies of the carbonate and evaporite cycles is correlative with the prodelta facies of the clastic cycles. If this is correct, then it becomes possible to correlate events on land, such as increased runoff or tectonic pulses, with the rhythms of sea-level change.

If we assume that glacio-eustatic sea-level changes were the dominant cause of Paradox cyclicity and using the comparative analysis of the cycles from the evaporite and clastic facies, it is possible to gain a better understanding of the genesis of the black shales, which form the important source rocks in the Paradox basin. For example, during an interglacial period when melting ice sheets in the southern hemisphere brought sea level to its highest stand, climatic response in the Paradox region seems to have been increased precipitation. This resulted in maximum runoff from the land. However, the heavy rainfall probably created a lush growth of vegetation that would have minimized erosion. This would explain why only fine-grained clastics and an abundance of terrestrial plant debris reached the Paradox sea at this time. The siliciclastics plus terrestrial plant remains were deposited as a prodelta facies near shore and as a black-shale facies further out in the basin. The black shales were probably deposited from density currents that moved out over heavy residual brines still trapped in the basin from the previous evaporitic phase. This stratification of the water column allowed only clay-sized sediment to reach the inner basin, and at the same time provided a depositional environment that was strongly reducing and anoxic. With the beginning of a new glacial period, sea level would begin to fall and the climate on shore would be characterized by aridity. This would have caused a loss of vegetative cover and a consequent acceleration of erosion even though runoff volume was smaller and probably periodic. With a drop in sea level, the streams would seek a new base level and cut down through the exposed and previously deposited prodelta facies. Coarse clastics could then be deposited in distributary stream channels and along delta fronts which prograded basinward as sea level continued to fall. As the ice sheets attained their maximum volume, and sea level was at its lowest stand, extremely arid conditions would have induced deposition of evaporites in the basin and ended the runoff and clastic transport from the land area.

In summary, the principle conclusions suggested by the preceeding interpretation are:

1) The black-shale facies of the basin grades into a fan delta complex on the southeast edge of the basin.
2) Most of the siliciclastics in the black-shale facies are from fluviatile contributions.
3) A large amount of terrestrial plant debris should be present in the black-shale facies.
4) Melting and growth of continental ice sheets in the southern hemisphere caused eustatic sea-level changes, which controlled the chemical facies of the Paradox cycles. At the same time, climatic change related to glacial or interglacial stages controlled runoff and transport of siliciclastics from the land.

STRATIGRAPHIC DISTRIBUTION OF ORGANIC CARBON

In the GD-1 core hole, total organic carbon (TOC) determinations were made on 241 samples which tested almost all of the most organic-rich intervals in the Pennsylvanian sequence (Table 1). These samples were selected for analysis on the basis of their dark color with the exception of a small group specifically selected to include all of the evaporite lithologies. The first significant TOC values (> 1.0 percent) were found near the top of the Lower Member of the Hermosa Formation (Pinkerton Trail). This interval, which is about 90 ft (27.4 m) thick, consists of a penesaline facies of thin anhydrites, dolostones, and gray- to dark-gray shales. Several shale samples from this interval had TOC values of over 2 percent. Unfortunately, poor core recovery in this interval may have precluded sampling of some of the richest layers.

The most consistently high TOC values were found in the black shales associated with the evaporite cycles of the Paradox Member. Some of these shales contain nearly 13 weight percent organic carbon, and have a decidedly sooty appearance. One of the richest shales (evaporite cycle 14) averaged about 8.6 percent TOC through an 8 ft (2.4 m) thick interval. Again in some of these shales, poor core recovery probably resulted in a loss of some of the richest layers.

Four intervals in the upper member of the Hermosa Formation (Honaker Trail Formation of Wengerd, 1958) contained significant amounts of TOC in the GD-1 core hole. Three of these intervals are at the base of the member and are elements of evaporite cycles 1, 2, and 3, which were placed in the upper member at this locality because the cycles do not contain halite. The shale in evaporite cycle 3 (lower Ismay) was sampled in considerable detail and through an interval of about 30 ft (9.1 m) it averaged about 2.5 percent TOC. This shale was also sampled in the ER-1 and SD-1 core holes (Figure 1). A comparison of the TOC distribution in these three core holes shows that GD-1 and SD-1 have a similar pattern with highest values near the top of the interval (Figure 8). In the ER-1 hole the organic-rich interval thickens and shows higher TOC values near the base of the shale. The fourth interval of high TOC values is a 32 ft (9.7 m) thick sequence of black coaly shales near the top of the upper member. Two samples from this interval contained 12.67 and 21.12 weight percent TOC.

TYPE OF ORGANIC MATTER

As described in the proceeding sections an evaporite basin, such as the Paradox, can be expected to produce large amounts of organic matter from algae and bacteria. An additional source of organic matter includes marine plankton that are swept into the basin by the seawater influx that replaces evaporation losses. Thus, it has generally been assumed that the type of organic matter contained in Pennsylvanian source rocks, associated with the evaporite facies of this basin was entirely sapropelic. Evidence is now available that suggests that a large volume of organic matter may also have been contributed to this basin from terrestrial sources.

The type of organic matter in the Hermosa Formation varies considerably with stratigraphic position and is a major factor in determining the quality (gas or oil) and quantity of hydrocarbons produced during catagenesis. During catagenesis, marine kerogen generally produces two to three times more bitumen (oil) than coaly (type III) kerogen. Based on microscopic examination, the black shales near the top of the Upper Member are the most coaly of the Pennsylvanian sequence. The genetic potential of those uppermost rocks is as high as 74 kg/ton which according to Tissot and Welte (1978) is indicative of excellent source rock potential. However, since the kerogen is mostly type III, this interval might

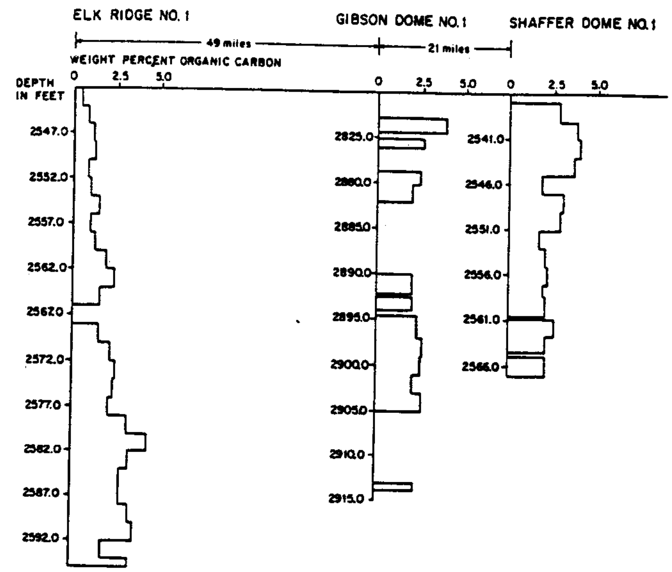


Figure 8. Distribution of total organic carbon (TOC) in the black shale of evaporite-carbonate cycle 3 ("Gothic") in the ER-1, GD-1, and SD-1 core holes.

be expected to produce minimal oil but considerable gas. Source rocks near the base of the Upper Member and in the Paradox Member contain a more hydrogen-rich kerogen. Pyrolysis data (H_2 and O_2 indexes) from this interval (Table 2), when plotted on a modified van Krevelen diagram, follows an evolutionary path, suggesting a mixture of types II and III kerogen (Figure 9). The atomic H/C and O/C ratios for the kerogen in these same rocks in the GD-1 and SV-3 core holes (Table 3 and Figure 10), also suggest a mixture of types II and III. Ratios of the steranes (Table 4) lend further support to classification of kerogen in this stratigraphic interval. $\frac{\alpha\alpha+\beta\beta\ C_{27}}{\alpha\alpha+\beta\beta\ C_{29}}$

THERMAL HISTORY AT THE GD-1 LOCATION

The Paradox basin lies entirely within the Colorado Plateau. According to Reiter and others (1979), the apparent uniformity of heat flow in the interior of the plateau suggests the lack of significant crustal thermal sources. The well known tectonic stability of the Colorado Plateau block may have also imparted a high degree of thermal stability. Recent studies by Bodell and Chapman (1982) show that although there are areas of high-heat flow (81-89 mWm^{-2})[1] around the plateau periphery, there is a large interior thermal low (58-61 mWm^{-2}). These same authors also suggest that heat flow in the area surrounding Monticello and Blanding, Utah, which would include the location of the GD-1 core hole, is between 50 and 60 mWm^{-2}. Local igneous activity some 25 m.y. ago formed laccolithic complexes (Abajo, La Sal, Ute, and Henry Mountains) in the interior area of low-heat flow. However, if as Bodell and Chapman suggest there is a lag of 15-20 m.y. between magma formation and increased heat-flow response, then it might be assumed that present day heat flow probably represents maximum heat-flow conditions since the inception of the Paradox basin.

Assessment of the thermal history at the GD-1 well site is greatly facilitated by the fact that detailed temperature profiles have been measured on at least two separate occasions over a 2-year period since the hole was drilled (Sass and others, 1983). The geothermal profile obtained from these measurements suggests an average gradient of about

Table 1. Organic carbon content and vitrinite reflectance data for samples from the Hermosa Formation in the GD-1 core hole, Paradox basin

[leaders (–) indicate no data]

Depth (ft)	Stratigraphic interval	Lithology	Organic carbon (wt.%)	Vitrinite reflectance (R_o)
		Upper Member of Hermosa Formation (Honaker Trail)		
1404.2 - 1404.7	–	coaly shale	12.67	0.74
1411.0 - 1413.0	–	silty limestone	1.07	–
1428.0 - 1430.2	–	coaly shale	21.12	0.56
1496.8 - 1497.2	–	calcareous shale	0.63	0.59
1497.1 - 1497.4	–	----do----	1.08	–
1505.8 - 1507.2	–	argillaceous limestone	0.18	0.68
1641.5 - 1643.6	–	silty shale	0.22	–
1886.5 - 1887.7	–	calcareous, silty shale	2.16	–
1987.0 - 1989.0	–	argillaceous limestone	0.12	–
1991.0 - 1993.0	–	----do----	0.22	–
1993.0 - 1994.9	–	argillaceous limestone	0.34	–
2001.0 - 2002.6	–	----do----	0.27	–
2010.5 - 2011.3	–	calcareous siltstone	0.25	–
2030.7 - 2032.6	–	silty shale	0.14	–
2034.0 - 2035.4	–	calcareous siltstone	0.46	–
2106.0 - 2108.0	–	calcareous siltstone	0.11	–
2162.0 - 2164.0	–	----do----	0.32	–
2225.0 - 2227.0	–	----do----	0.26	–
2377.0 - 2379.0	–	silty limestone	0.56	0.38
2402.0 - 2403.8	–	----do----	0.29	–
2435.5 - 2437.5	–	argillaceous limestone	0.40	–
2445.5 - 2446.5	–	silty limestone	1.10	–
2486.0 - 2488.0	–	----do----	0.96	–
2495.8 - 2498.0	–	----do----	1.22	–
2618.7 - 2621.0	–	calcareous siltstone	0.56	–
2629.0 - 2630.1	–	calcareous siltstone	0.59	–
2639.9 - 2642.0	–	----do----	0.99	–
2644.0 - 2645.8	–	----do----	0.70	–
2650.0 - 2652.0	–	----do----	0.97	–
2654.0 - 2655.3	–	calcareous shale	0.87	–
2657.0 - 2658.2	–	silty calcareous dolomite	0.83	–
2658.2 - 2660.0	–	----do----	0.67	–
2667.0 - 2669.6	–	silty calcareous shale	1.82	–
2672.0 - 2674.0	–	calcareous shale	1.45	–
2677.7 - 2679.1	–	silty calcareous shale	1.46	–
2682.3 - 2683.9	–	silty calcareous dolomite	0.57	–
2756.0 - 2758.3	Upper Ismay	silty dolomite	0.55	–
2758.3 - 2760.0	----do----	silty dolomite and shale	3.10	0.45
2760.0 - 2762.0	----do----	calcareous shale	2.41	–
2761.0 - 2764.4	----do----	calcareous silty shale	1.42	–
2771.5 - 2773.2	Upper Ismay	silty calcareous shale	2.15	–
2773.2 - 2775.0	----do----	calcareous shale	1.82	–
2775.0 - 2776.4	----do----	----do----	2.11	–
2776.0 - 2779.0	----do----	----do----	2.31	–
2779.0 - 2781.0	----do----	silty calcareous shale	2.89	–
2781.0 - 2783.0	Upper Ismay	calcareous shale	3.93	–
2783.0 - 2783.7	----do----	----do----	4.15	–
2786.6 - 2878.6	Lower Ismay	silty dolomite	0.28	–
2880.9 - 2882.0	----do----	calcareous shale	2.55	–
2884.5 - 2886.0	----do----	calcareous silty shale	2.36	–
2886.0 - 2887.9	Lower Ismay	calcareous silty shale	1.89	–
2890.0 - 2892.3	----do----	----do----	1.95	0.51
2892.6 - 2894.0	----do----	----do----	1.97	–
2894.6 - 2897.0	----do----	----do----	2.34	–
2897.0 - 2899.0	----do----	----do----	2.56	–

Depth (ft)	Stratigraphic interval	Lithology	Organic carbon (wt. %)	Vitrinite reflectance (R_o)
2899.0 - 2901.0	Lower Ismay	calcareous silty shale	2.52	-
2901.0 - 2903.0	—do—	—do—	1.96	-
2903.0 - 2905.0	—do—	—do—	2.64	-
2907.0 - 2907.8	—do—	silty calcareous shale	2.21	-
		Paradox Member of Hermosa Formation		
2942.2 - 2944.1	Cycle 4	silty dolomite	0.38	-
2951.2 - 2953.0	—do—	silty calcareous shale	1.03	-
2954.7 - 2956.0	—do—	silty dolomite	0.08	-
2961.0 - 2961.7	—do—	—do—	0.07	-
2965.0 - 2967.0	—do—	—do—	0.09	-
3068.7 - 3070.3	Cycle 5	silty dolomite	0.11	-
3075.0 - 3077.0	Cycle 5	—do—	0.35	-
3079.4 - 3081.0	—do—	—do—	0.17	-
3086.9 - 3089.0	—do—	—do—	0.14	-
3108.9 - 3109.7	—do—	silty dolomitic shale	1.46	-
3252.8 - 3252.9	Cycle 6	carnallitic halite	0.51	-
3264.0 - 3264.1	—do—	—do—	0.05	-
3275.5 - 3275.6	—do—	halite	0.18	-
3281.0 - 3281.1	—do—	—do—	0.18	-
3295.5 - 3296.0	—do—	—do—	0.17	-
3302.8 - 3302.9	Cycle 6	halite	0.15	-
3314.2 - 3314.8	—do—	—do—	0.14	-
3326.7 - 3327.8	—do—	—do—	0.34	-
3331.2 - 3331.9	—do—	—do—	0.07	-
3343.8 - 3344.5	—do—	—do—	0.05	-
3355.0 - 3356.1	Cycle 6	halite	0.09	-
3364.0 - 3365.3	—do—	silty dolomite	0.42	-
3516.7 - 3517.1	Cycle 8	dolomite	0.29	-
3531.8 - 3533.0	—do—	dolomitic silty shale	0.55	-
3538.0 - 3540.0	—do—	dolomitic siltstone	0.37	-
3706.2 - 3707.7	Cycle 9	dolomitic silty shale	2.78	-
3843.3 - 3844.2	Cycle 10	silty dolomite	0.57	0.36
3847.7 - 3849.0	—do—	silty shale	7.68	-
4042.1 - 4042.7	cycle 13	calcareous shale	1.10	-
4046.0 - 4048.0	—do—	silty dolomite	0.66	-
4048.0 - 4050.0	Cycle 13	silty, calcareous dolomitic shale	2.02	-
4050.0 - 4052.0	—do—	—do—	12.86	0.51
4052.0 - 4054.0	—do—	—do—	11.11	-
4054.0 - 4056.0	—do—	—do—	9.65	-
4056.0 - 4056.4	—do—	—do—	8.59	-
4055.6 - 4055.9	Cycle 13	silty, calcareous dolomitic shale	5.53	-
4055.9 - 4056.4	—do—	—do—	7.15	-
4057.0 - 4057.7	—do—	—do—	5.15	-
4057.7 - 4058.2	—do—	silty dolomite	0.23	-
4062.0 - 4063.7	—do—	silty calcareous shale	1.95	-
4139.0 - 4141.0	Cycle 14	silty dolomite	0.14	-
4194.3 - 4194.4	Cycle 15	halite	0.39	-
4194.4 - 4194.6	—do—	—do—	0.31	-
4194.4 - 4194.6	—do—	—do—	0.31	-
4194.6 - 4194.7	—do—	—do—	0.22	-
4194.7 - 4194.8	Cycle 15	halite	0.33	-
4194.8 - 4194.9	—do—	—do—	0.20	-
4194.9 - 4195.0	—do—	—do—	0.32	-
4195.0 - 4195.1	—do—	—do—	0.36	-
4195.1 - 4195.2	—do—	—do—	0.21	-
4195.2 - 4195.3	Cycle 15	halite	0.08	-
4196.8 - 4196.9	—do—	—do—	0.08	-
4197.0 - 4197.1	—do—	—do—	0.03	-
4197.1 - 4197.2	—do—		0.12	-
4217.0 - 4219.0	—do—	silty dolomitic shale	1.30	-

Depth (ft)	Stratigraphic Interval	Lithology	Organic carbon (wt. %)	Vitrinite reflectance (R_o)
4973.4 - 4975.3	Cycle 19	silty, calcareous dolomitic shale	2.51	0.42
4975.6 - 4978.0	----do----	silty dolomite	0.19	-
5233.1 - 5224.6	Cane Creek	anhydritic calcareous shale	1.66	-
5227.8 - 5228.7	----do----	dolomitic anhydrite	0.12	-
5234.7 - 5236.4	----do----	----do----	0.25	-
5238.5 - 5238.9	Cane Creek	dolomitic silty shale	3.96	-
5240.9 - 5243.0	----do----	silty dolomitic shale	2.11	0.54
5252.0 - 5254.0	----do----	silty dolomitic calcareous shale	0.90	-
5260.0 - 5262.0	----do----	silty calcareous dolomitic shale	0.42	-
5268.0 - 5268.4	----do----	dolomitic silty anhydrite	0.17	-
5426.6 - 5427.1	Cycle 24	silty calcareous shale	5.62	-
Lower Member of the Hermosa Formation (Pinkerton Trail)				
5551.7 - 5552.6	-	silty argillaceous limestone	0.93	0.55
5561.0 - 5563.0	-	silty dolomite and anhydrite	0.64	-
5563.0 - 5565.0	-	dolomitic silty limestone	0.50	-
5565.0 - 5567.0	-	dolomitic siltstone	0.81	0.56
5571.0 - 5572.6	-	silty argillaceous limestone	1.35	-
5580.2 - 5582.0	-	silty argillaceous limestone	2.86	-
5603.0 - 5605.2	-	calcareous siltstone	0.19	-
5605.2 - 5607.0	-	limestone	0.26	-
5608.6 - 5609.5	-	----do----	3.44	-
5646.0 - 5648.0	-	silty dolomitic limestone	2.55	-
5648.0 - 5650.0	-	silty limestone	2.48	-
5662.3 - 5664.0	-	calcareous siltstone	0.16	-
5664.0 - 5665.0	-	calcareous siltstone	0.46	-
5680.3 - 5682.1	-	calcareous silty shale	1.10	-
5690.1 - 5692.0	-	argillaceous limestone	.05	-
5695.0 - 5696.0	-	silty shale	1.33	-
5704.0 - 5706.0	-	silty calcareous shale	0.10	-
5706.0 - 5708.0	-	----do----	0.42	-
5710.0 - 5712.0	-	----do----	0.37	-

1.04°F/100 ft (19.0°C/km) (Figure 11). The bedrock surface at the GD-1 hole is stratigraphically near the Permian-Triassic boundary. For this part of the Paradox basin, at least an estimated 8,000 ft (2435 m) of Mesozoic strata were originally present (Molenaar, p. 126, 1981) necessitating an appropriate adjustment to arrive at actual burial temperatures effecting Pennsylvanian source rocks. Adjusting for the eroded Mesozoic section, and assuming that the present day thermal gradient is representative of the paleo gradient, an estimated paleo burial temperature for the top of the Pennsylvanian sequence in the GD-1 hole should have been about 123°F (50.6°C) and 169.5°F (76.7°C) for the base.

KEROGEN MATURATION

Maturation of kerogen in the Pennsylvanian rocks penetrated by the GD-1 core hole was studied by means of vitrinite reflectance, Rock Eval pyrolysis, extraction and gas chromatography-mass spectrometry. These data suggests that hydrocarbon generation or catagenesis began at about 1,400 ft (609 m) in the GD-1 hole. Adding back the eroded Mesozoic section this gives a paleo-burial depth of about 9,400 ft (2862 m). Going back to the previous section and the suggested geothermal gradient of 1.04°F/100 ft (19.0°C/km), the paleo-burial depth of beginning catagenesis would correspond to a paleo-temperature of 125°F (51.7°C). This fits well with the temperature of beginning catagenesis in Paleozoic rocks of many other basins (Tissot and Welte, 1978).

The stage of kerogen evolution in a source rock can be measured by using transformation ratios which are derived from Rock-Eval pyrolysis data. As defined by Tissot and Welte (1978) the transformation ratio is the ratio of hydrocarbons already generated in the rock (S_1) to the genetic potential ($S_1 + S_2$). Genetic potential is the total amount of hydrocarbons the kerogen in a rock is capable of forming by pyrolysis. Transformation ratios are generally low (<0.1) above the zone of catagenesis, but progressively increase with depth and have a value of 1.0 at the point where the kerogen has been essentially reduced to graphite.

Transformation ratios (Table 2) for rocks of the Hermosa Formation in the GD-1 core hole containing >1.0 percent TOC suggest that the kerogens in the Upper Member are immature, whereas, those in the Paradox Member are mature. However, the sudden increase in ratios at the top of the Paradox Member cannot be accounted for by depth induced thermal maturation. It seems more likely that high transformation ratios in the Paradox Member are related to the fact that these source rocks are sealed in above and below by halite, which prevented migration of hydrocarbons. Source rocks at the base of the Upper Member lack these evaporite seals and are adjacent to somewhat more permeable strata. Consequently, these rocks have somewhat low ratios be-

Table 2. Rock-Eval pyrolysis data from samples from the GD-1 core hole

[Analyst, T.A. Daws, U.S. Geological Survey]

Sample interval (in ft)	Organic carbon (wt. %)	T_{max} (°C)	S_1 (mgHC/g)	S_2 (mgHC/g)	S_3 ($mgCO_2/g$)	Genetic potential (S_1+S_2)	H_2 Index (mgHC/gC)	O_2 Index ($mgCO_2/gC$)	Transformation ratio (S_1/S_1+S_2)
Upper Member (Honaker Trail)									
1428.0 - 1430.2	21.12	433	1.27	72.69	1.05	73.96	344	5	0.02
1886.9 - 1887.7	2.97	444	0.01	3.35	0.53	3.36	113	18	0.00
2247.0 - 2249.0	0.34	434	0.05	0.21	0.32	0.27	62	94	0.19
2445.5 - 2246.5	1.01	443	0.17	0.60	0.29	0.77	59	29	0.22
2758.3 - 2760.0	2.85	450	1.18	12.46	0.83	13.64	437	29	0.09
2878.6 - 2880.3	4.15	450	1.17	18.11	0.92	19.28	436	22	0.06
Paradox Member									
2951.2 - 2953.0	1.03	435	0.53	2.35	0.62	2.88	228	60	0.18
3108.9 - 3109.7	1.46	431	2.91	6.90	0.63	9.91	472	43	0.29
3370.3 - 3372.0	6.63	434	3.72	21.38	3.78	25.10	322	57	0.15
3530.5 - 3530.8	6.25	440	3.28	21.32	0.86	24.60	341	14	0.30
3847.7 - 3849.0	8.45	447	7.13	24.06	0.58	31.19	285	7	0.13
4050.0 - 4052.0	12.86	445	16.21	49.33	1.28	65.54	384	10	0.23
4352.2 - 4353.4	0.70	439	0.28	1.14	3.47	1.42	163	496	0.25
4751.0 - 4753.0	2.94	425	1.21	3.33	2.53	4.54	113	86	0.27
4973.4 - 4975.3	2.50	443	2.28	7.42	1.49	9.70	297	60	0.24
4995.0 - 4996.2	0.76	427	1.11	2.09	0.79	3.20	275	104	0.35
5238.5 - 5238.9	3.96	438	4.15	15.27	1.04	19.42	386	26	0.21
5426.6 - 5427.1	5.62	449	4.67	9.59	1.33	14.26	170	24	0.33
Lower Member (Pinkerton Trail)									
5590.0 - 5592.0	0.88	441	0.25	1.86	0.05	2.11	211	57	0.12
5605.2 - 5607.0	0.26	571	0.03	0.12	0.16	0.15	46	62	0.20
5689.1 - 5692.0	0.05	532	0.02	0.35	0.53	0.37	700	1060	0.05

cause hydrocarbons generated in place have probably migrated out of this interval. This interpretation is also supported by the fact that source rocks within the evaporite sequence are commonly overpressured whereas those above the evaporites are not.

Extraction data consisting of extractable organic matter (EOM) and extractable hydrocarbons (EHC) were obtained from six-black-shale samples in the ER-1, GD-1, and KIS-1 core holes (Table 4). Three of these samples were from the same stratigraphic interval ("Gothic"), but from different depths and holes. The other three samples are from the GD-1 hole from evaporite-carbonate cycles 2, 10, and the "Cane Creek". All the samples from the ER-1 and GD-1 holes had high EOM/TOC and EHC/TOC ratios suggesting that these stratigraphic intervals are mature and have excellent source rock potential. The EOM/TOC and EHC/TOC ratios in the KIS-1 sample ("Gothic") were lower than the ratios from the same stratigraphic interval in the GD-1 and ER-1 holes. These lower ratios may be the result of migration and loss of hydrocarbons, increased maturity, or differences in types of organic matter and depositional environment. The saturate to aromatic (S/A) hydrocarbon and n-C_{17}/pristane ratios (Table 4) for the shales in the basal part of the Upper Member (includes the "Gothic") suggests that these samples are mature in holes ER-1 and GD-1 and more mature in the KIS-1 hole.

$$\frac{\Sigma\ \beta\beta\ C_{29}}{\Sigma\ \alpha\alpha + \Sigma\beta\beta\ C_{29}}$$

However, the steranes and C_{31} (22S/22R) and C_{33}(22S/22R) extended hopane ratios (Table 4) suggest that the Gothic samples in all three holes have the same order of maturity (Figure 12). Comparison of gas chromatograms of the saturated hydrocarbon fraction from the three "Gothic" samples shows striking differences in the KIS-1 sample (Figure 13). For example, the latter is much lower in regular isoprenoids (i.e., pristane, phytane, farnesane, etc.) and higher in non-isoprenoids branched alkanes relative to n-alkanes, than either of the other two "Gothic" samples. The difference in branched alkane content may, in part be due to increased maturation at the KIS-1 location (the Kis-1 sample is at least 3,000 ft deeper than stratigraphically equivalent samples from GD-1 and ER-1). A more plausible explanation may involve a different source of organic matter. This is supported by the fact that a sample from 5,238.5 ft (1594.7 m) in the GD-1 hole has an isoprenoid fingerprint that is nearly identical to the shallower "Gothic" samples in GD-1 and ER-1.

Vitrinite reflectance values (R_o) for rocks of the Hermosa Formation in the GD-1 core hole ranged from 0.36 to 0.74 percent (in oil), and show little relationship to depth (Table 5). Considering that an R_o range of 0.5 to 0.7 is the approximate boundary most frequently used to represent the beginning of oil generation, then the source rocks in the Paradox Member should be in the early stage of catagenesis. This assessment is contradicted by the previously discussed pyrolysis data which show these rocks to be well within the oil window and,

[1] 41.84 mWm^2 = 1 HFU (heat flow unit)
1 HFU = 10×10^{-6} calories/cm^2-sec

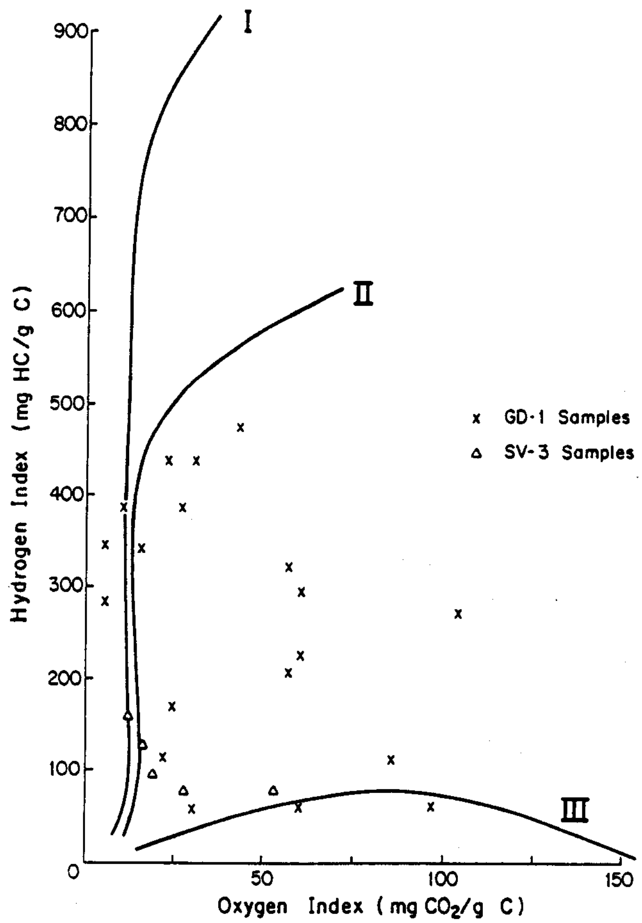


Figure 9. Hydrogen and oxygen indexes determined by pyrolysis for samples from the Hermosa Formation plotted on a van Krevelen diagram.

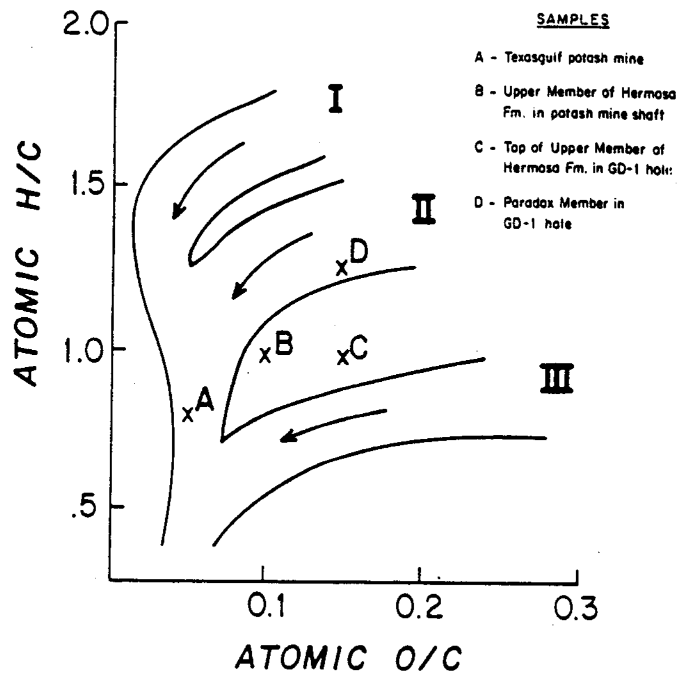


Figure 10. H/C and O/C atomic ratios in kerogen samples from the Hermosa Formation plotted on a modified van Krevelen diagram.

thus, strong suppression of R_o is indicated. Unpublished data by B.F. Reuger, U.S. Geological Survey, on palynomorph collections from the Paradox Member in the GD-1 core hole also provides evidence which suggests R_o values in the Paradox Member are suppressed. The palynomorphs exhibit a well defined progressive change in color, or thermal alteration index (TAI), with increasing depth of burial (Table 5). The color change from yellow brown at the top, to brown dark brown at the base of the Paradox Member suggests an increase in maturity from moderately mature to mature. From these data, it

Table 3. Elemental analyses of kerogen from Pennsylvanian rocks of the Hermosa Formation in the Paradox basin.

[leaders (-) indicate no data]

Sample, locality, and stratigraphic interval	Lithology	C	H	O	N	S	H/C	C/O	Atomic H/C	Atomic O/C
Ore zone, Texasgulf potash mine, Paradox Member	coal	81.37	5.33	9.47	0.73	0.17	0.65	8.65	0.78	0.049
Texasgulf potash mine shale, 1,850 ft, Upper Member	coaly shale	60.96	4.62	8.23	1.26	1.62	0.76	7.4	0.91	0.101
GD-1, 1,428 ft, Upper Member	coaly shale	21.90	1.77	4.33	0.49	-	0.81	5.1	0.97	0.148
GD-1, 4,050 ft, Paradox Member	black shale	17.53	1.80	3.51	0.69	-	1.03	5.0	1.23	0.150
SV-3, 1,668 ft, Paradox Member	black shale	67.18	3.65	-	1.31	-	0.54	-	0.65	-
SV-3, 1,867 ft, Paradox Member	black shale	54.07	3.10	-	1.39	-	0.57	-	0.69	-
SV-3, 1,896 ft, Paradox Member	black shale	44.33	2.69	-	0.78	-	0.61	-	0.73	-
SV-3, 2,489 ft, Paradox Member	black shale	59.63	4.41	-	1.88	-	0.73	-	0.89	-
SV-3, 3,763 ft, Paradox Member	black shale	71.56	4.07	-	1.92	-	0.57	-	0.68	-
SV-3, 3,801 ft, Paradox Member	black shale	64.36	3.58	-	1.63	-	0.56	-	0.67	-
SV-3, 3,977 ft, Paradox Member	black shale	64.28	3.72	-	1.77	-	0.58	-	0.69	-

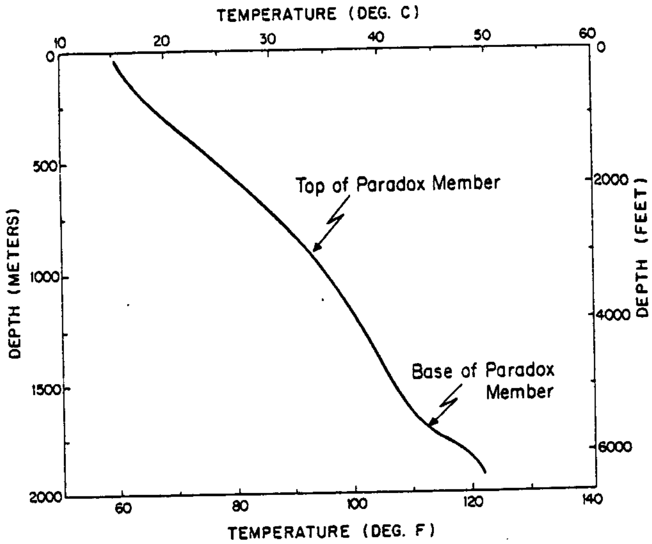


Figure 11. Temperature profile in the GD-1 core hole. From Sass and others (1983).

seems reasonable to conclude that vitrinite reflectance in samples from the Paradox Member is strongly suppressed. Vitrinite reflectance suppression on a similar scale has been observed by the authors in other bitumen-rich samples such as the oil shales of the Green River Formation of the Uinta basin of Utah and the Piceance Creek basin of Colorado. The magnitude of the problem of vitrinite reflectance suppression has been emphasized and thoroughly reviewed by Price and Barker (in press). These authors show that retardation of R_o values can be expected where vitrinite and exinite macerals are associated. According to Price and Barker, maturation rates are proportional to the hydrogen content of macerals, with deeper burial being required for hydrogen-rich material. They also suggest that hydrogen enrichment and oxygen depletion is an early part of diagenesis, and may be the result of bacterial reworking of organic matter in anoxic environments. One of the surprising features of the black shales of the Paradox Member is the abundance of vitrinite in rock that might normally be expected to contain primarily type I or II kerogen. Furthermore, these shales are oil prone and show relatively high hydrogen indexes. Since these characteristics are not generally associated with vitrinitic macerals (type III kerogen), the Price-Barker theory offers an appealing solution to the problem.

GENETIC POTENTIAL

The previously discussed extraction data shows that the genetic potential of many of the petroleum source rocks (black shales) in the Hermosa Formation is quite high. One of the thickest and most widespread of these black shales is the "Gothic". This shale is about 32 ft (9.6 m) thick in the GD-1 core hole. A representative sample from this interval at a depth of 2,897-2,899 ft (882-882.5 m) indicates the shale has already generated a large amount of hydrocarbons (Table 4). The extractable organic matter (EOM) from this interval (Table 4) is 5,086 ppm consisting of hydrocarbons heavier than C_{15}. This figure can be increased by at least 50 percent to account for the low boiling liquid hydrocarbons lost during isolation of the $C_{15}+$ EOM. Accordingly, the calculated inplace EOM value for this sample based on adjustment for the 50 percent loss is 7,629 ppm. Assuming this shale has a density of about 2.2×10^9 metric tons/km^3 its petroleum potential can be calculated as follows:

Weight of source rock/km^2
9.6 m (thickness) x 1 km^2 (area) x 2.2 10^9 metric tons km^3 (density) = 2.1 x 10^7 metric tons
Metric tons oil in place per km^2
2.1 x 10^7 metric tons/km^2 (from above) x 0.7629 wt % (EOM) = 161,124 metric tons
161,124 x 7.64 bbls/metric ton (conversion factor API 40° oil) = 1,230,991 bbls/km^2
or
4,970 bbls/acre

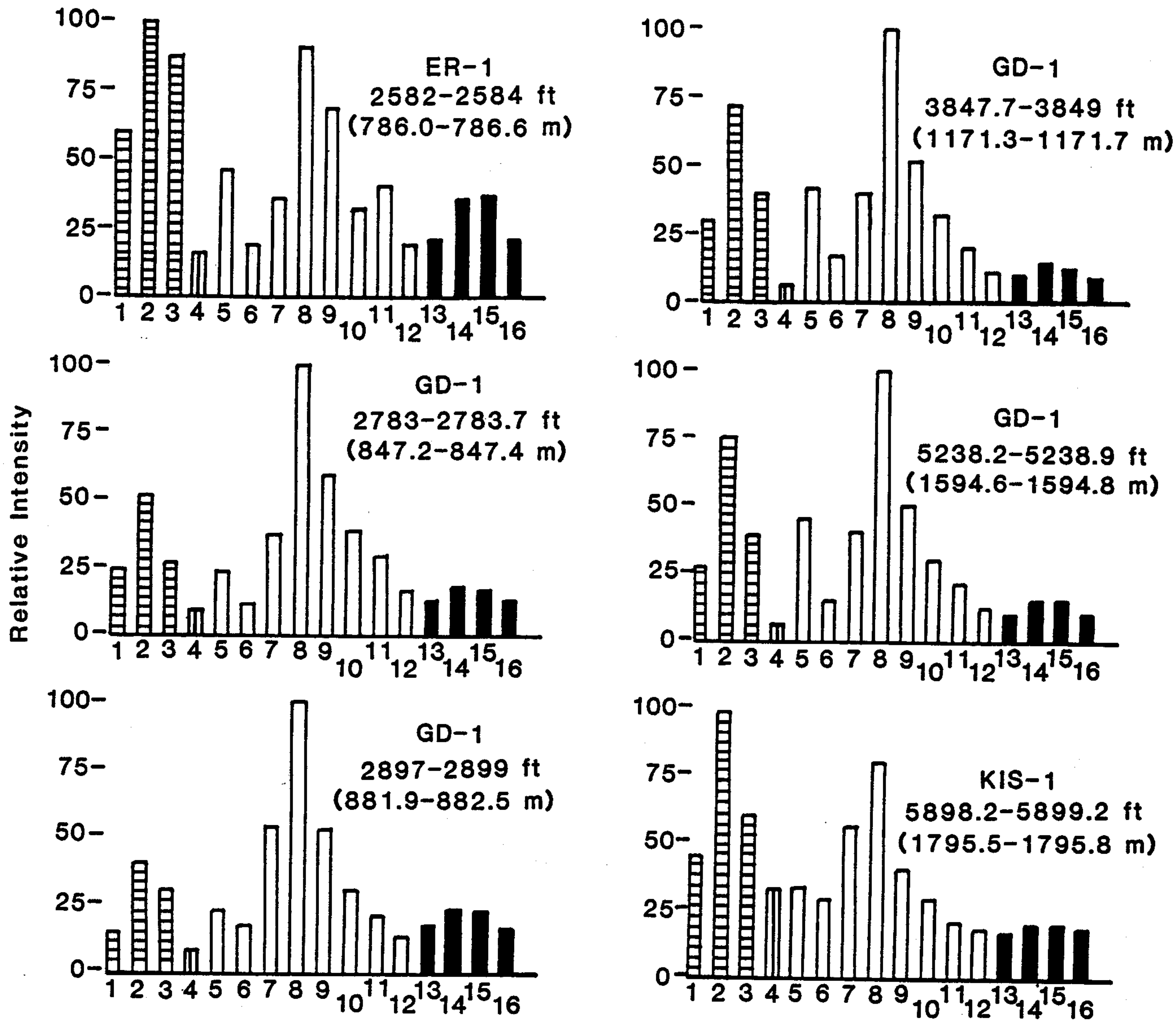
Pyrolysis data (Table 2) for another sample from this same interval show a low transformation ratio (0.06) and as previously stated this suggests a large loss of hydrocarbons by migration.

Table 4. Extraction, gas chromatography and gas chromatography-mass spectrometry results from Upper Member and Paradox Member and Upper Member and Paradox Member Pennsylvanian source rocks of the Paradox basin.

				Extraction							Gas Chromatography		Gas Chromatography-Mass Spectrometry			
Well	Stratigraphic Unit	Depth ft.	TOC %	EOM/TOC mg/g	EHC/TOC mg/g	EOM ppm	SAT ppm	AROM ppm	RESINS ppm	S/A	n-C_{17}/Pristane	Pristane/Phytane	C_{27} Reg Ster./C_{29} Reg Ster.	I88/(Iαα+I88)	C_{31} 22S/22R	C_{33} 22S/a22R
ER-1	Upper Member "Gothic"	2582-2584	3.3	293	207	9538	5238	1502	2086	3.5	1.7	1.1	1.4	0.6	1.3	1.3
GD-1	Upper Member	2783-2783.7	4.2	119	79	4947	2538	726	1468	3.5	1.5	1.4	1.4	0.6	1.6	1.6
GD-1	Upper Member "Gothic"	2897-2899	2.6	198	140	50p86	3033	563	1311	5.4	1.8	1.2	1.3	0.6	1.7	1.7
GD-1	Paradox Member	3847-3849	8.5	164	119	13902	7989	2136	989	3.7	2.0	1.3	1.4	0.6	1.6	1.6
GD-1	Paradox Member	5238.2-5238.9	4.0	328	266	13119	10053	1326	1770	7.6	2.5	1.3	1.4	0.6	1.6	1.6
KIS-1	Upper Member "Gothic"	5898.2-5899.2	1.3	50	41	655	501	34	150	14.7	7.1	1.3	1.1	0.5	1.4	1.3

1 $\frac{\text{Iαα 20S and 20R + I88 20S and 20R } (C_{27} \text{ Reg Steranes})}{\text{Iαα 20S and 20R + I88 20S and 20R } (C_{29} \text{ Reg Steranes})}$

2 $\frac{\text{I88 20S and 20R } (C_{29} \text{ Reg Steranes})}{\text{Iαα 20S and 20R + I88 20S and 20R } (C_{29} \text{ Reg Steranes})}$



BIOMARKERS

1) C_{21} Tricyclic
2) C_{23} Tricyclic
3) C_{24} Tricyclic
4) C_{24} Tetracyclic
5) Trisnorneohopane(Ts)
6) Trisnorhopane (TM)
7) Norhopane (C_{29})
8) Hopane (C_{30})
9) C_{31} Extended Hopane (22S)
10) C_{31} Extended Hopane (22R)
11) C_{33} Extended Hopane (22S)
12) C_{33} Extended Hopane (22R)
13) $5\alpha,14\alpha,17\alpha,20S$ C_{29} Sterane
14) $5\alpha,14\beta,17\beta,20R$ C_{29} Sterane
15) $5\alpha,14\beta,17\beta,20S$ C_{29} Sterane
16) $5\alpha,14\alpha,17\alpha,20R$ C_{29} Sterane

Figure 12. Biomarkers in the saturated hydrocarbon fractions extracted from source rocks in the Hermosa Formation.

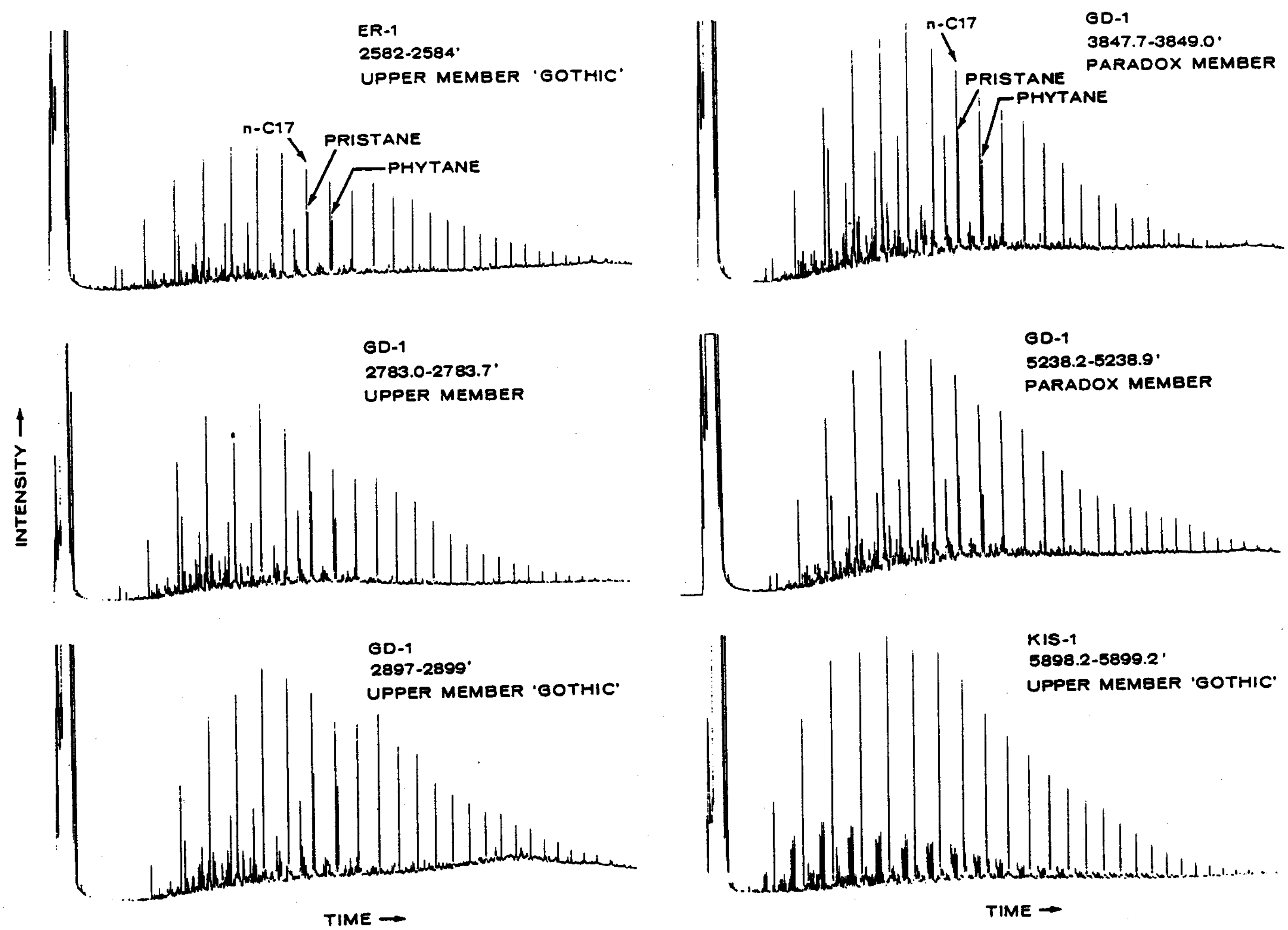


Figure 13. Chromatograms of the saturated hydrocarbon fractions extracted from shale samples in the Hermosa Formation.

Thus, the above calculated potential for the "Gothic" is probably very conservative. In the KIS-1 hole which is located (Figure 1) much closer to the clastic source area than the GD-1 or ER-1 holes the "Gothic" is 50 ft (15.2 m) thick. Unfortunately, only one sample from the "Gothic" was available for analysis from this hole. This sample has an organic carbon content of 1.3 percent and an extractable organic matter content of 655 ppm (Table 4). On the basis of this one sample, we can only speculate about whether these lower values truly represent a regional diminishing of the genetic potential of the "Gothic" in this part of the basin. Dilution of the kerogen in the shale by an increase in clastic content owing to the proximity of the source area may be expected. It is also possible that the kerogen in this shale becomes predominately type III near the source area which would further lower the generation capacity. However, the great thickness of the "Gothic" along the southeast edge of the Paradox basin (> 160 ft) may compensate for the speculated reduction in quality.

Other black shales in the Hermosa Formation, especially those associated with the evaporite facies of the Paradox Member, have very high genetic potentials, but are usually less than 15 ft (4.6 m) thick. One of these shales (evaporite cycle 14) in the GD-1 core hole has an organic carbon content of 12.86 percent and on the basis of Rock-Eval data the hydrocarbons already in the rock (S_1) are 16,210 ppm (Table 2). This shale is about 8 ft (2.4 m) thick in the GD-1 core hole and the calculated oil-in-place potential for this unit is about 653,898 bbls/km^2 (2,640 bbls/acre). During drilling, numerous wells in the Paradox basin have encountered abnormally pressured zones of oil, gas, and brine in these black shales and associated dolostones. These over-pressured conditions can be explained as the result of the generation of large volumes of hydrocarbons, which are almost totally retained in the source rocks, because of an enclosing seal of halite layers.

CONCLUSIONS

The evaporite-carbonate cycles of the Hermosa Formation contain black shales that are rich in organic matter. Where these rocks have paleo-burial depths of 10,000 ft (3044 m) or more, they have generated large volumes of petroleum. Some of the major conclusions reached in this brief and preliminary investigation of these important source rocks are:

(1) The black shales in the evaporite cycles of the Paradox Member are, in part, probably correlative with a prodelta facies in clastic cycles present in the Silverton fan delta complex on the southeast edge of the basin.

(2) Eustatic sea-level changes caused by melting or growing ice sheets in the southern hemisphere were the probable control of cyclicity in the evaporite facies. Climatic conditions affected by glacial and interglacial periods may have controlled runoff and erosion, thus, allowing con-

Table 5. Vitrinite reflectance (R_o) and thermal alteration index (TAI) data from Pennsylvanian rocks in the GD-1 core hole, Paradox basin, Utah

[leaders (–) no data]

Sample depth (in ft)	R_o	TAI
1401.2	0.74	–
1428.0	0.56	–
1496.8	0.59	–
1505.8	0.68	–
2377.0	0.38	–
2758.3	0.45	–
2890.0	0.51	–
2981.8	–	yellow-yellow-brown
3249.9	–	----do----
3312.2	–	----do----
3324.1	–	yellow-yellow-brown
3377.5	–	yellow-brown
3399.7	–	yellow (very thin spore)
3421.3	–	yellow-brown
3435.2	–	dark-yellow-brown
3843.3	0.36	–
3924.5	–	brown
4050.0	0.51	–
4147.8	–	brown
4716.3	–	----do----
4856.3	–	brown
4954.2	–	brown-dark brown
4973.4	0.42	–
5113.8	–	brown-dark brown
5138.0	–	----do----
5211.3	–	brown-dark brown
5240.9	0.54	–
5313.3	–	brown-dark brown
5514.2	–	----do----
5380.3	–	----do----
5462.3	–	brown-dark brown
5485.3	–	----do----
5503.2	–	----do----
5551.7	0.55	–
5565.0	0.56	–

comitant deposition of specific elements in both the land and the sea cycles.

(3) The Silverton fan delta complex may offer a large and relatively undrilled objective for petroleum exploration where thick black shales from the evaporite basin intertongue with delta front and distributary channel sandstones.

(4) Vitrinite reflectance (R_o) in the black shales of the paradox Member is strongly suppressed. In rock samples where all other parameters indicate mature conditions the R_o values are frequently <0.50 percent.

(5) The kerogen in the black shales of the evaporite-carbonate cycles is a mixture of types II and III. A major component of terrestrial plant material may have been derived as the result of fluviatile influxes from the Silverton fan delta.

(6) The black shales in some of the evaporite cycles are extremely rich source rocks. Total organic carbon content reaches 12 percent in some shale and generated hydrocarbons may exceed 16,000 ppm. Most of this petroleum is still locked up in the source rocks because of enclosing evaporite seals. Vertical leakage of hydrocarbons around the depositional edge of the evaporite facies in many cycles may be a significant factor to consider in future exploration in the Paradox basin.

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HYDROCARBON SOURCE ROCKS OF THE GREATER ROCKY MOUNTAIN REGION

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